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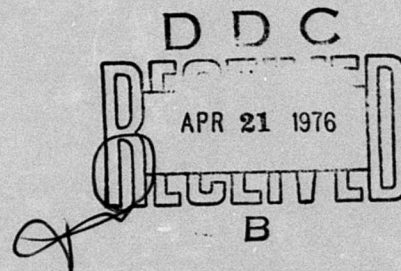| AUTHORITY |
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TELEMETRY SYSTEM PARAMETERS

AND BIT ERROR PERFORMANCE

OF NRZ AND DM PCM/FM

(AIRTASK A5355352 054D 5W47410030, Work Unit A535210000002)

By

D. A. KING
Instrumentation Development Division

29 March 1976

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PACIFIC MISSILE TEST CENTER

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This report describes work performed under AIRTASK A5355352 054D 5W47410030, Missile Flight Evaluation Systems, Work Unit A535210000002.

Mr. F. R. Hartzler, Head, Component Development Branch, and **Mr. K. L. Berns**, Head, Instrumentation Development Division, have reviewed this report for publication.

Released by:
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Telemetry Project Manager

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1.   The following should be added to page 3: bit synchronizer A was the EMR 720 and bit synchronizer B was the Monitor 335.

2.   This information was not included in the text of the report to avoid the possibility of construing the results as a comparison of the two bit synchronizers.

W. J. KIRKPATRICK
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The work reported herein involved the experimental determination of optimum telemetry system parameters for the transmission of NRZ and DM PCM/FM. The objective was to compare the efficiency of the two PCM formats and to evaluate rules of thumb for determining system parameters. A PCM/FM telemetry system was simulated and optimum receiver IF bandwidth, RF transmitter deviation, and premodulation filter bandwidth for the transmission of NRZ and DM were determined so that NRZ and DM performance could be compared on an equivalent basis.

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20. ABSTRACT (Concluded)

NRZ and DM rules of thumb were examined to determine the system performance loss due to non-optimum operation.

The experiment verified other reported conclusions that show NRZ to be 3 dB better than DM for equicalent bit rates under their respective optimum conditions. Thus DM is not recommended for epplications of meximum data trensfer in e bandlimited RF system where noisy signels mey be received. Use of rules of thumb in setting system parameters will generally result in less than 3 dB degradetion in BEP as long as the rules fell within certain bounds about optimum:

1.   The receiver IF bandwidth should be at least twice the optimum (f_B for NRZ, $2f_B$ for DM) for data-recording purposes. The equivelent bendwidth of the prerecording and post-recording IF combinetion should be close to f_B but less than $2f_B$ for NRZ and close to $2f_B$ but less than $4f_B$ for DM.

2.   The peak-to-peek RF trensmitter devietion should lie between $0.6f_B$ and $0.9f_B$ for NRZ end between $1.2f_B$ and $1.8f_B$ for DM.

3.   The premodulation filter bendwidth should fall between $0.5f_B$ end $1.0f_B$ for both NRZ end DM.

ACKNOWLEDGMENT

CONTENTS

ABBREVIATIONS

AGC	Automatic gain control
BEP	Bit error probability
BW	Bandwidth
dB	Decibels
dBm	Decibels with reference to 1 milliwatt
DM	Delay modulation (or Miller code)
f_B	Bit rate
FM	Frequency modulation
F/S	Filter/sample bit detector
FSK	Frequency shift keying
GHz	Gigahertz
I/D	Integrate and dump bit detector
IF	Intermediate frequency
IRIG	Inter-Range Instrumentation Group
kb/s	Kilobits per second
kHz	Kilohertz
Mb/s	Megabits per second
MHz	Megahertz
NRZ	Non-return-to-zero
PCM	Pulse code modulation
P-P	Peak-to-peak
RF	Radio frequency
SNR	Signal-to-noise ratio

TELEMETRY SYSTEM PARAMETERS AND BIT ERROR PERFORMANCE OF NRZ AND DM PCM/FM

(AIRTASK A5355352 054D 5W47410030,
Work Unit A535210000002)

By
D. A. KING

SUMMARY

The work reported herein involved the experimental determination of optimum telemetry system parameters for the transmission of NRZ and DM PCM/FM. The objective was to compare the efficiency of the two PCM formats and to evaluate rules of thumb for determining system parameters. A PCM/FM telemetry system was simulated and optimum receiver IF bandwidth, RF transmitter deviation, and pre-modulation filter bandwidth for the transmission of NRZ and DM were determined so that NRZ and DM performance could be compared on an equivalent basis. NRZ and DM rules of thumb were examined to determine the system performance loss due to non-optimum operation.

The experiment verified other reported conclusions that show NRZ to be 3 dB better than DM for equivalent bit rates under their respective optimum conditions. Thus DM is not recommended for applications of maximum data transfer in a bandlimited RF system where noisy signals may be received.

The experimental optimum values of RF transmitter deviation, IF filter bandwidth, and premodulation filter bandwidth were found to be:

	NRZ		**DM**	
	F/S	I/D	F/S	I/D
P-P RF Transmitter Deviation	$0.8f_B$	$0.9f_B$	$1.6f_B$	$1.8f_B$
IF Filter Bandwidth	$1.0f_B$	$1.0f_B$	$2.0f_B$	$2.0f_B$
Premodulation Filter Bandwidth	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$

Use of rules of thumb in setting system parameters will generally result in less than 3 dB degradation in BEP as long as the rules fall within certain bounds about optimum:

1. The receiver IF bandwidth should be at least twice the optimum for data-recording purposes. The equivalent bandwidth of the prerecording and post-recording IF combination should be close to f_B but less than $2f_B$ for NRZ and close to $2f_B$ but less than $4f_B$ for DM.

2. The peak-to-peak RF transmitter deviation should lie between $0.6f_B$ and $0.9f_B$ for NRZ and between $1.2f_B$ and $1.8f_B$ for DM.

3. The premodulation filter bandwidth should fall between $0.5f_B$ and $1.0f_B$ for both NRZ and DM.

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INTRODUCTION

An experiment was conducted on a simulated RF telemetry link to compare the bit error performance characteristics of two PCM formats, delay modulation (DM or Miller code) and non-return-to-zero (NRZ). A valid comparison required that the telemetry system be operated in an optimum manner such that bit errors for both PCM signals were minimized for equivalent data transfer. Consequently, this report is also concerned with establishing optimum values for NRZ and DM system parameters. There were four parameters under control in the simulated telemetry link with which to minimize the bit errors: the PCM format, the premodulation filter bandwidth, the RF transmitter deviation, and the receiver IF bandwidth. All other system parameters were held constant during the experiment.

The criterion for optimality was that combination of parameter values for each of the two codes which minimized their bit error probability (BEP). However, optimum parameter values for minimizing BEP may not be optimum from the viewpoint of RF bandwidth considerations. To remain within an RF channel assignment, the trading of more bit errors for a narrower RF signal bandwidth may be necessary. This tradeoff can be accomplished by decreasing the RF transmitter deviation and premodulation filter bandwidth from their optimum values. Both RF bandwidth and minimization of BEP were considered in this experiment. The work was performed under AIRTASK A5355352 054D 5W47410030, Missile Flight Evaluation Systems, work unit A535210000002, to provide analytical support to the Telemetry Group of the Range Commanders Council.

TEST EQUIPMENT

The simulated telemetry system and associated test equipment are shown in figure 1. The equipment is listed in table 1.

The EMR 721 test set served as both a bit error rate detector and an NRZ and DM signal generator with variable bit rate. The NRZ and DM signals were pseudo-random sequences of 2,047 bits. The premodulation filter was a four-pole, linear phase filter with adjustable bandwidth. RF transmitter deviation and RF attenuation were adjustable on the FM signal generator which was operated at a carrier frequency of approximately 1.48 GHz. The receiver IF bandwidth was selectable from the following fixed units: 100 kHz, 200 kHz, 500 kHz, 750 kHz, and 1.0 MHz. The receiver's video filter was bypassed and the video signal applied directly to one of two bit synchronizers. Bit synchronizer A contained both a $0.75f_B$ matched filter/sample bit detector and an integrate and dump detector. Bit synchronizer B contained only an integrate and dump detector. The selected bit synchronizer returned the recovered NRZ and DM bit streams to the EMR 721 for error detection. RF bandwidth was monitored on a spectrum analyzer.
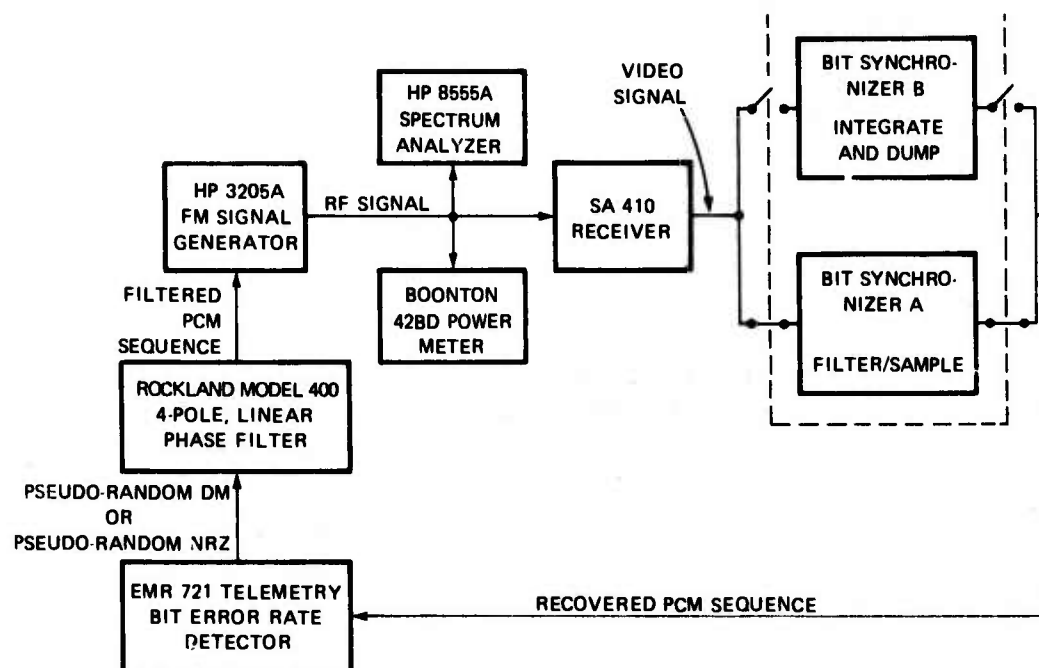
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Figure 1. System Block Diagram.

Table 1. Equipment List

Bit error rate detector, EMR 721
Bit synchronizers A and B, two state-of-the-art bit synchronizers
Premodulation filter, Rockland model 1200
FM signal generator, HP 3205A
Receiver, Scientific-Atlante series 410 WA
Oscilloscope, Tektronix type 564
Spectrum Analyzer, HP 8555A
Microwattmeter, Boonton Electronics 42 BD

TEST METHODS AND RESULTS

The system parameters for NRZ and DM were first optimized for minimum BEP and then RF bandwidth considerations were examined. The initial parameter values were set according to the following commonly used rules of thumb:

	NRZ	DM
P-P RF Transmitter Deviation	$0.7f_B$	$1.2f_B$
Premodulation Filter Bandwidth	$0.6f_B$	$0.6f_B$
Receiver IF Bandwidth	f_B	$2.0f_B$

where f_B is the bit rate.

RF Transmitter Deviation

The optimum RF transmitter deviations for NRZ and DM were found by fixing the attenuation of the RF signal such that the BEP was approximately 10^{-4}. The deviation and BEP were recorded as the

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deviation was incrementally varied at the transmitter so that BEP variations were adequately defined. Increasing the RF attenuation in 2 dB steps and repeating the deviation and BEP measurements resulted in a family of curves from which the optimum deviation could be determined. Figure 2 for NRZ and figure 3 for DM show the BEP variations with RF transmitter deviation for f_B equal to a 500 kb/s rate. This data shows that the optimum deviations are ±200 kHz at the 500 kb/s rate for NRZ and ±400 kHz for DM. NRZ bit rates of 200 kb/s and 750 kb/s were also investigated and their optimum deviations were found to be ±80 kHz and ±300 kHz, respectively. DM bit rates of 100 kb/s and 375 kb/s were investigated and their optimum deviations were also found to be ±80 kHz and ±300 kHz, respectively. In general, the data indicate that the optimum peak-to-peak RF transmitter deviations are $0.8f_B$ for NRZ and $1.6f_B$ for DM with the other parameters at their initial values.

A research of available literature on optimum deviation for NRZ PCM/FM shows a variation ranging from $0.7f_B$ to $0.9f_B$. Kotel'nikov (reference 1) and Smith (reference 2) derive the optimum deviation to be $0.715f_B$ for FSK. Experimentally, Aeronutronic (reference 3) found the optimum deviation to be $0.75f_B$ as did a study by Electro-Mechanical Research (EMR) (reference 4). At the other end of the range, Shaft (reference 5) calculated $0.796f_B$ and experimentally found $0.84f_B$ as the optimum values.

Perhaps one of the more likely reasons for the variation in optimum deviation is the method of bit detection. In this experiment a $0.75f_B$ matched filter/sample detector in bit synchronizer A resulted in optimum deviations of $0.8f_B$ for NRZ and $1.6f_B$ for DM. An integrate and dump detector (square PCM matched filter) also in bit synchronizer A was tested for NRZ and gave $0.9f_B$ as optimum. Bit synchronizer B with a square PCM matched filter detector was also tested. Bit synchronizer B resulted in an optimum deviation of $0.9f_B$ for NRZ and $1.8f_B$ for DM. Aeronutronic's optimum of $0.75f_B$ (NRZ) was with an integrating detector. They also used a sampling detector that resulted in an optimum of $0.9f_B$ (NRZ). Kotel'nikov and Smith's optimum was derived for coherently detected FSK, whereas Shaft's optimum was determined using discriminator detection. The reason for the variation of optimum deviation with bit detector was not investigated, but, as shown in figures 2 and 3 and discussed later, the degradation in BEP due to a non-optimum deviation setting is not severe if maintained near optimum.

It was found that the optimum deviation is independent of the premodulation filter bandwidth but dependent upon IF bandwidth and IF signal-to-noise ratio (SNR). From figures 2 and 3 it appears that the optimum deviation increases roughly 10 percent at low IF SNR due to AGC action and/or changing IF filter characteristics (not all receivers exhibit this phenomena). However, this change causes a relatively insignificant increase in BEP and can probably be ignored.

The dependence of optimum deviation on IF bandwidth can be related to the RF signal and noise power spectrums. Figure 4(a) shows the RF signal spectrum with optimum RF deviation for a 500 kHz IF filter bandwidth (f_B = 500 kb/s). The IF bandwidth was doubled, and the optimum deviation was found no longer to be $0.8f_B$ but increased to $1.09f_B$ as shown in figure 4(c). Doubling the IF bandwidth doubled the noise power to the demodulator (assuming white noise), but as shown in a 1 MHz bandwidth of figure 4(a), the signal power contributed by the introduction of the second sidebands into the IF passband did not double the total signal power to the demodulator. Therefore, as a result of decreased IF SNR, the BEP increased. However, the doubled IF bandwidth then allowed the deviation to be increased up to $1.09f_B$ without BEP degradation due to intermodulation distortion (filter phase non-linearities) and forced FM thresholding (signal amplitude limiting by IF filter skirts). Increasing the deviation improves the receiver's video SNR and decreases the BEP. It does not increase the IF SNR. In fact, due to constant transmitter power, the spreading of the RF spectrum by increasing the deviation will lower the IF SNR by removing signal power from the passband. This power loss is not as significant as the improved video SNR, so consequently the net result is to lower the BEP as the deviation is increased to $1.09f_B$. Beyond $1.09f_B$, the BEP begins to increase again due to intermodulation distortion, signal power loss, and forced FM thresholding.
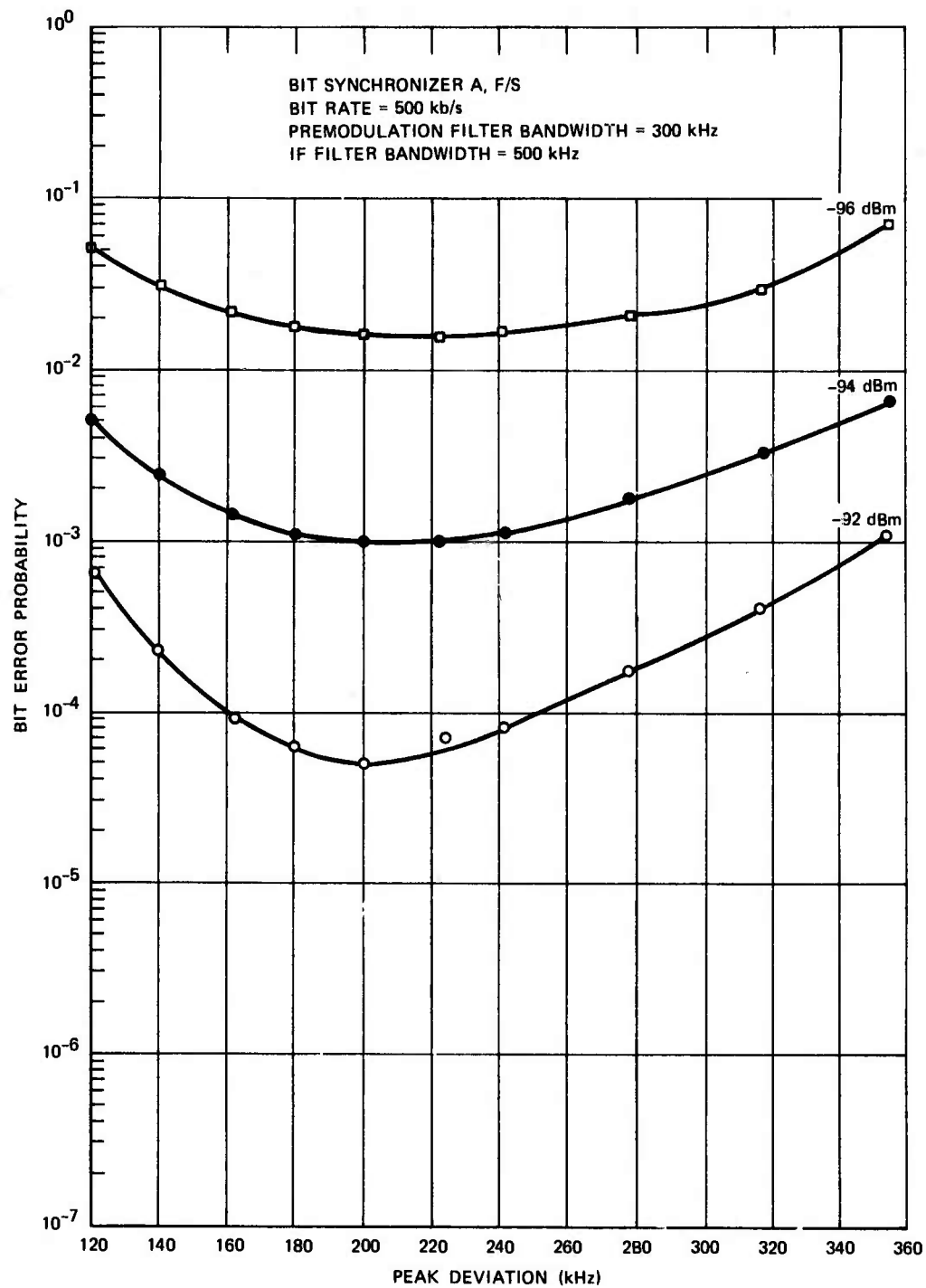
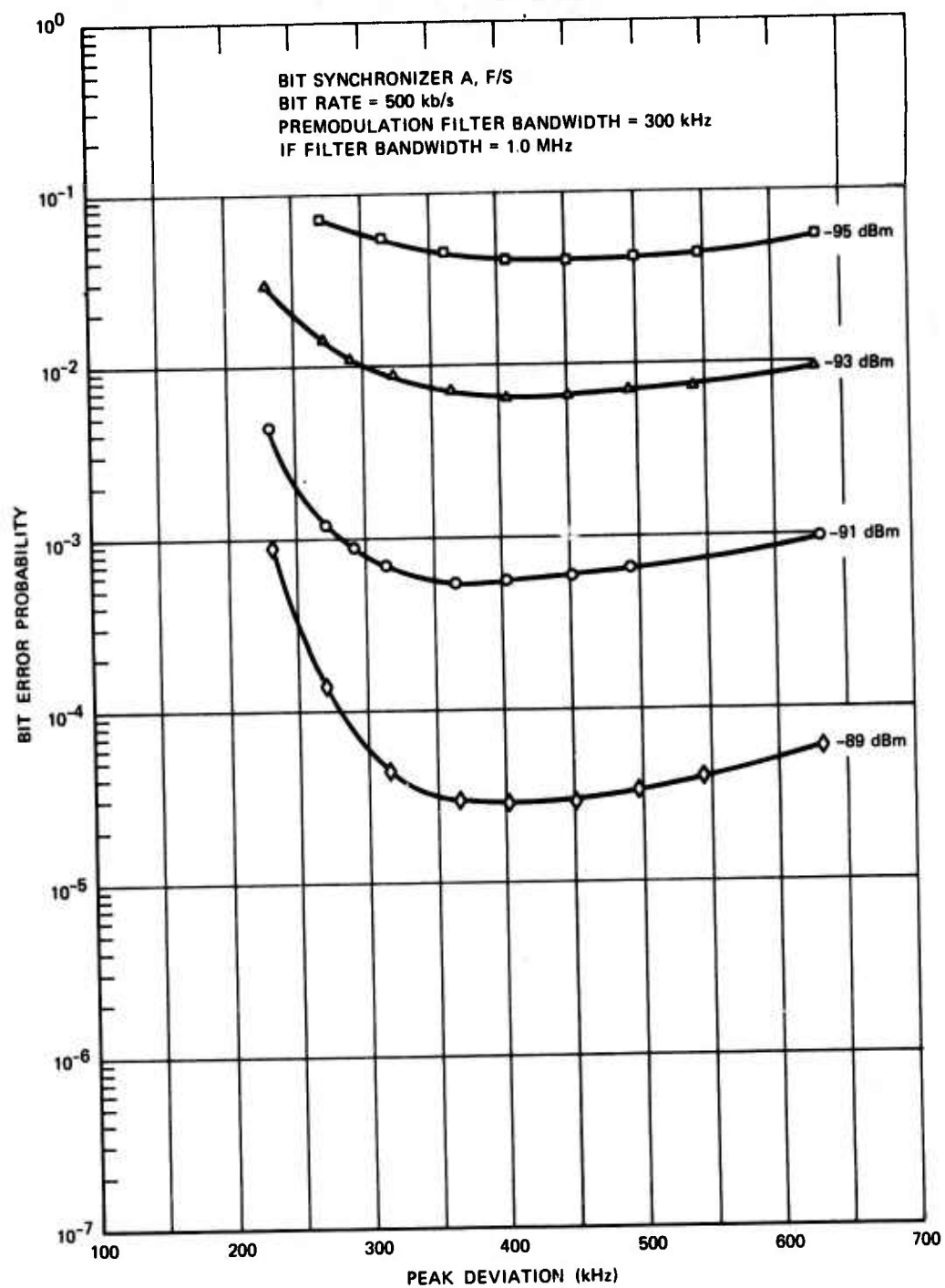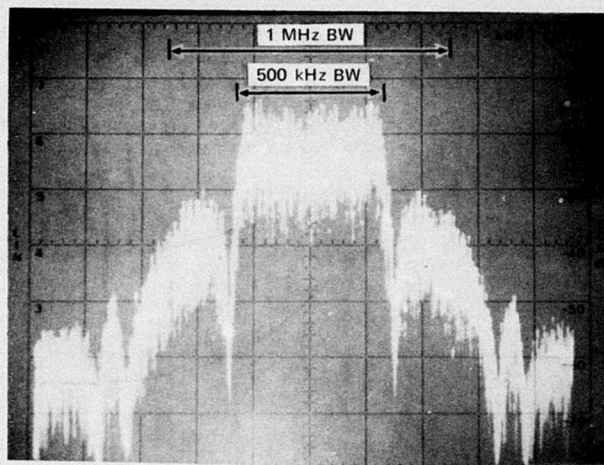Figure 2. BEP Variations With RF Deviation for NRZ PCM/FM.

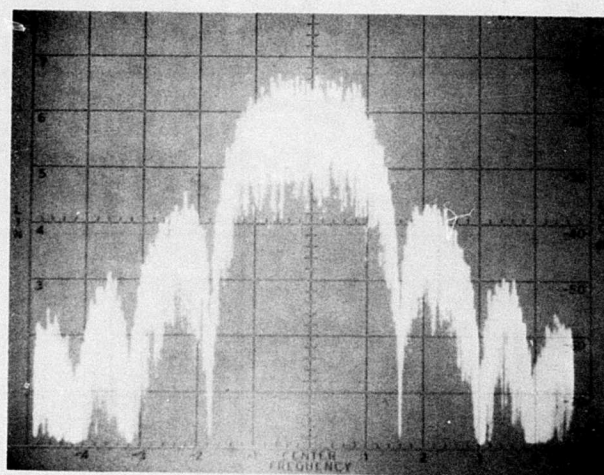Figure 3. BEP Variations With RF Deviation for DM PCM/FM.

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BIT SYNCHRONIZER A, F/S
500 kb/s NRZ
500 kHz PREMODULATION FILTER
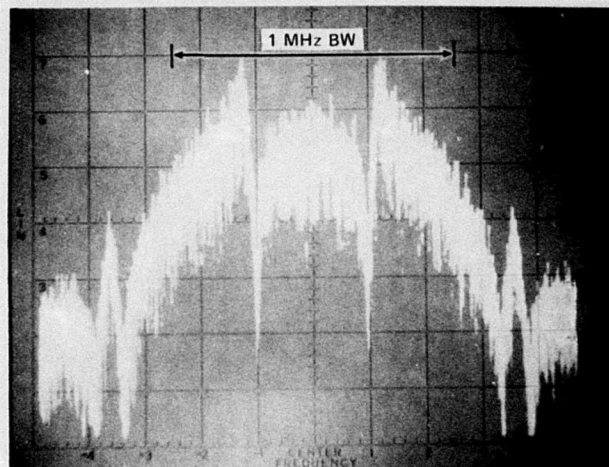200 kHz/DIVISION
0.8 f_B PEAK-TO-PEAK DEVIATION

(a)

BIT SYNCHRONIZER A, F/S
500 kb/s NRZ
500 kHz PREMODULATION FILTER
200 kHz/DIVISION
0.53 f_B PEAK-TO-PEAK DEVIATION

(b)

Figure 4. NRZ RF Signal Spectra.

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1 MHz BW

BIT SYNCHRONIZER A, F/S
500 kb/s NRZ
500 kHz PREMODULATION FILTER
200 kHz/DIVISION
1.09 f_B PEAK-TO-PEAK DEVIATION

(c)

Figure 4. (Concluded).

Obviously, if the IF bandwidth is halved from the 500 kHz of figure 4(a), the BEP will increase because of IF filter phase nonlinearities and forced FM thresholding. Reducing the deviation to remove these effects will lower the BEP. The experimental NRZ data in table 2 shows the optimum deviation for various IF bandwidths. All that remains in order to specify the optimum deviation is to determine the optimum IF bandwidth.

Table 2. NRZ Optimum Deviations for Various IF Filter Bandwidths

| Bit Rate (kb/s)	IF Filter Bandwidth (kHz)	Peak-to-Peak Deviation Ratio	Bit Synchronizer
100	100	0.77	A (F/S)
100	200	0.83	A (F/S)
100	300	1.38	A (F/S)
100	500	3.37	A (F/S)
750	500	0.75	B (I/D)
750	750	0.90	B (I/D)
750	1,000	1.09	B (I/D)

IF Bandwidth

In the experiments conducted by Aeronutronics (reference 3) and EMR (reference 4), the optimum receiver bandwidth for NRZ was investigated and found to be equal to the bit rate, f_B. An unpublished report on DM by Dr. W. R. Hedeman of Aerospace Corporation indicates an optimum bandwidth of $2f_B$ Their experiments were not repeated for this report.

A verification of these optimum bandwidths was conducted by visually examining the RF spectrums of NRZ and DM at various RF deviations and with the premodulation filter bandwidth equal to the bit rate. The RF signal spectra of figures 4 and 5 were taken with f_B equal to 500 kb/s. Figures 4(a) and 5(a) show RF signal spectra with optimum deviations for the optimum RF bandwidths reported above. The spectra are roughly flat and constant over a bandwidth equal to the bit rate and signal power drops abruptly outside this bandwidth. The 3-dB points of the optimum filter are thus located at
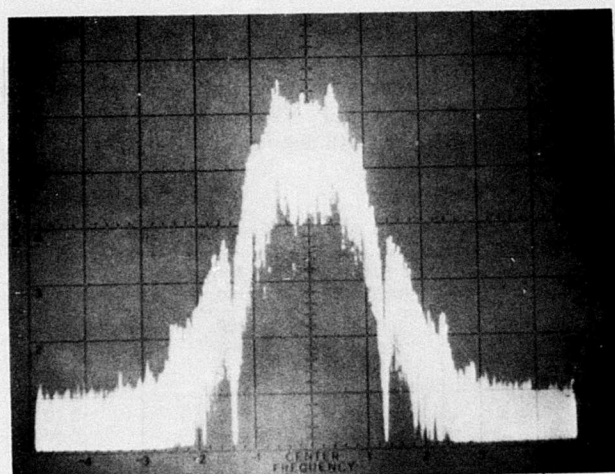
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BIT SYNCHRONIZER A, F/S
500 kb/s DM
500 kHz PREMODULATION FILTER
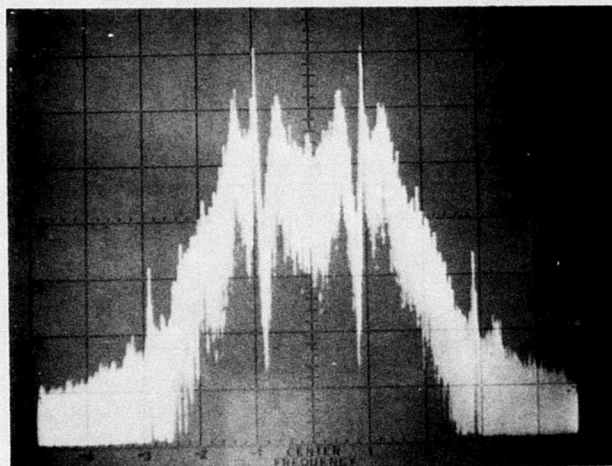200 kHz/DIVISION
1.6 f_B PEAK-TO-PEAK DEVIATION

(a)
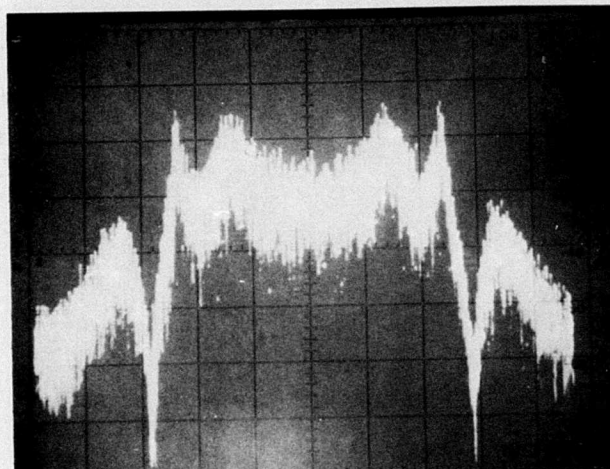
BIT SYNCHRONIZER A, F/S
500 kb/s DM
500 kHz PREMODULATION FILTER
500 kHz/DIVISION
1.04 f_B PEAK-TO-PEAK DEVIATION

(b)

Figure 5. DM RF Signal Spectra.

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BIT SYNCHRONIZER A, F/S
500 kb/s DM
500 kHz PREMODULATION FILTER
500 kHz/DIVISION
2.17 f_B PEAK-TO-PEAK DEVIATION

(c)

Figure 5. (Concluded).

a bandwidth equal to the bit rate for NRZ and twice the bit rate for DM; in this case, 500 kHz about center frequency for NRZ and 1,000 kHz about center frequency for DM. Both bandwidths encompass the first sidebands of the spectra where most of the signal power is concentrated. Larger bandwidths may allow more noise power than signal power into the IF passband and narrower bandwidths may unnecessarily restrict the signal causing intermodulation distortion and forced FM thresholding. Optimizing the RF deviation for a non-optimum IF bandwidth results in RF spectra such as those in figures 4(b) and 5(b) (narrower IF filter than optimum) and 4(c) and 5(c) (wider IF filter than optimum). These spectra are not as optimally distributed in the IF passband as in figures 4(a) and 5(a) and result in a higher BEP.

To illustrate the differences in BEP between optimum and non-optimum IF bandwidths and deviations, BEP variations with RF power were recorded and plotted in figures 6 and 7 for NRZ at 750 kb/s and for DM at 375 kb/s. BEP measurements were made using a 500 kHz, 750 kHz, and 1.0 MHz IF bandwidths with the RF deviation at optimum for 750 kHz and also with the RF deviation optimized for the non-optimum IFs. The results show severe BEP degradation for the narrower-than-optimum 500 kHz IF filter and an approximate 0.5 dB degradation for the wider-than-optimum 1.0 MHz filter for both NRZ and DM. Slight improvements in BEP were made by optimizing the RF deviation for the non-optimum IF filters, but the minimum BEP was still produced with the 750 kHz IF filter at a deviation of $0.9f_B$ (bit synchronizer B, I/D).

For data recording, the receiver IF bandwidth should be at least $2f_B$ for NRZ and $4f_B$ for DM to ensure no loss of signal because of IF clipping by signal drift. In such cases, the optimum RF deviation is set according to the total effective bandwidth of prerecording and post-recording IF's. Optimally, this effective bandwidth is set as close as possible to f_B for NRZ and $2f_B$ for DM.

Premodulation Filter Bandwidth

After setting the RF transmitter deviation and receiver IF bandwidth to the previously determined optimum values, the premodulation filter bandwidth was adjusted for minimum BEP. As expected, the optimum bandwidth was infinite for both NRZ and DM since signal energy per bit increases with
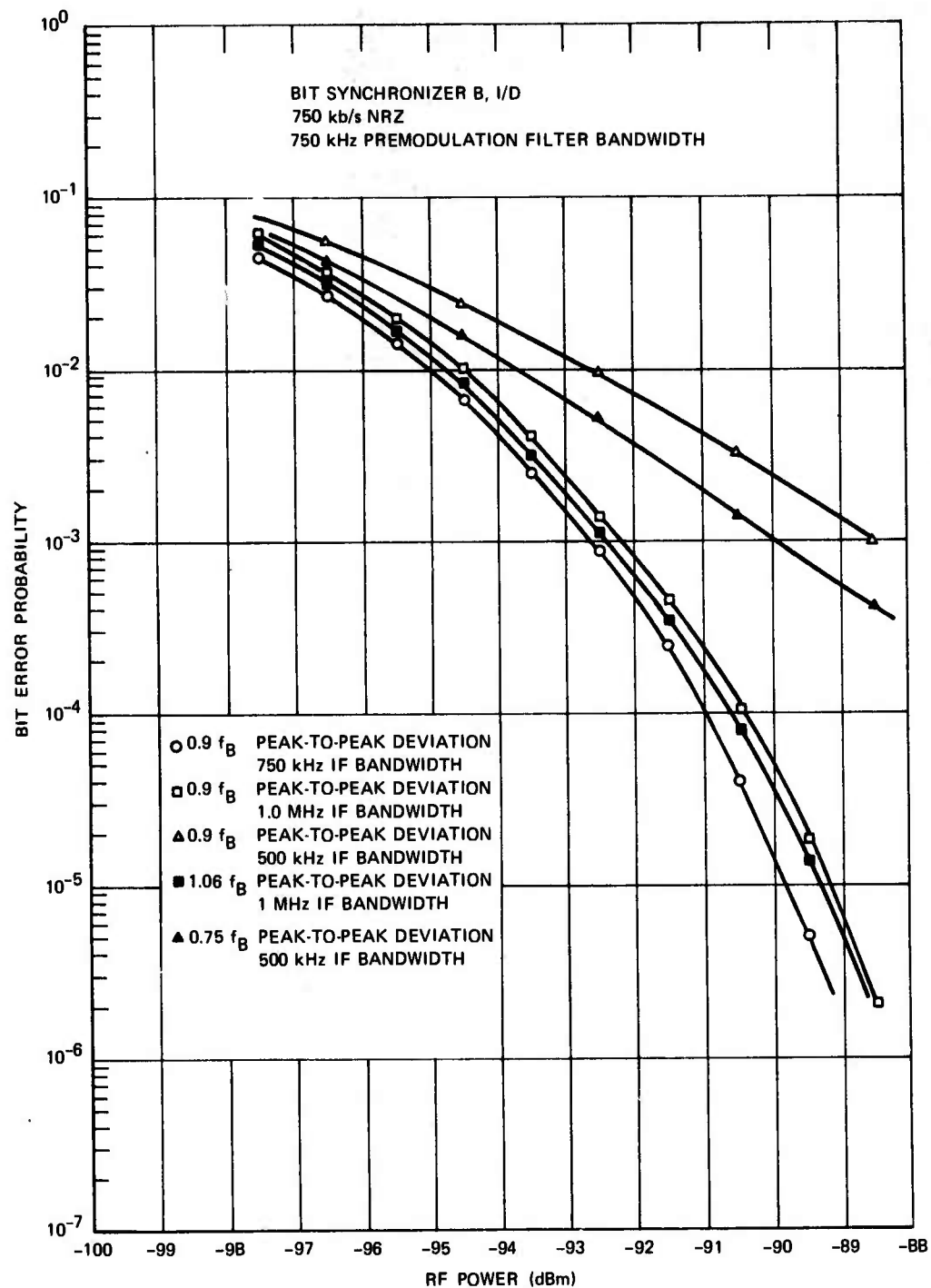
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Figure 6. NRZ Bit Error Sensitivity to IF Filter Bandwidth.
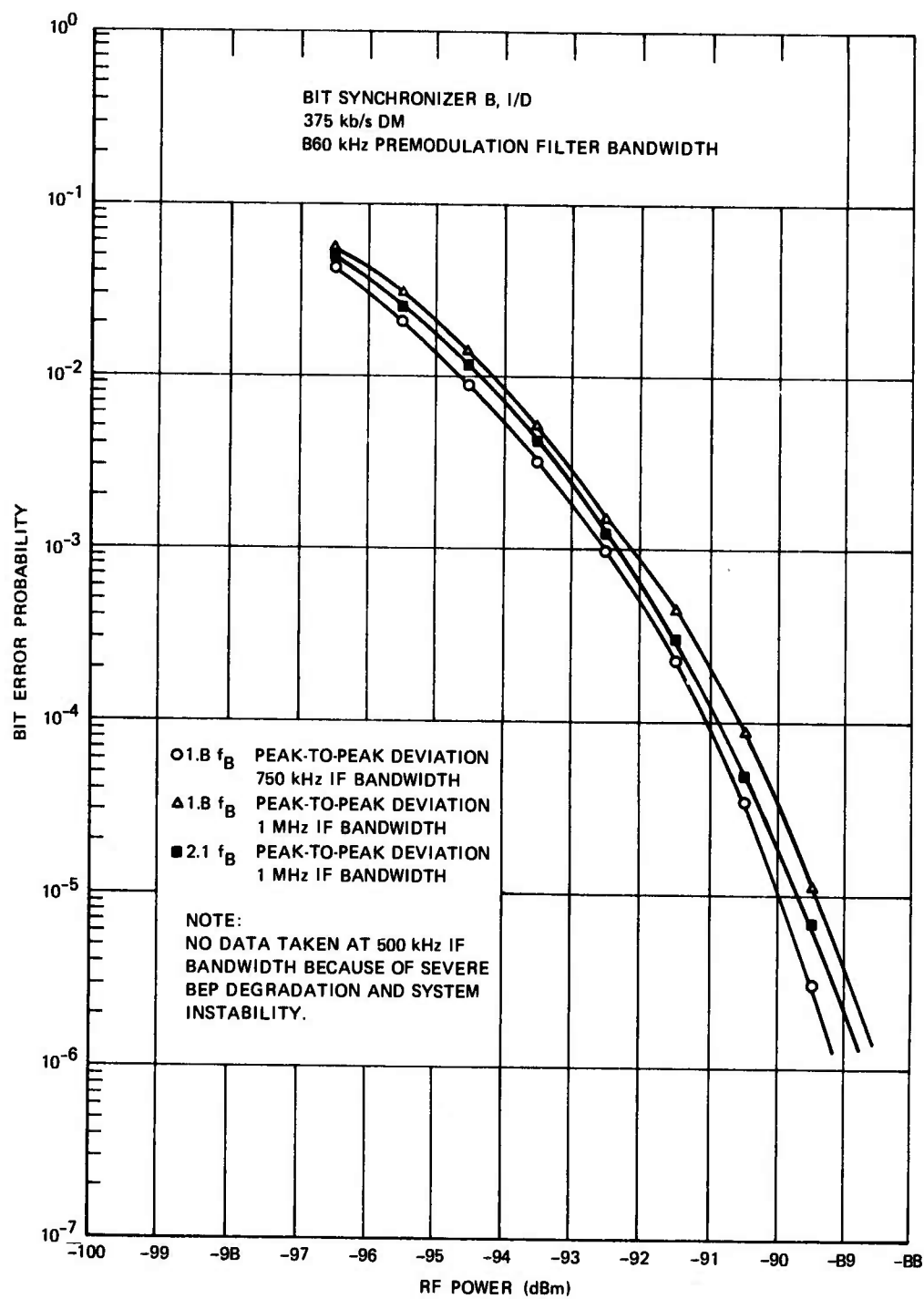
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Figure 7. DM Bit Error Sensitivity to IF Filter Bandwidth.

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bandwidth. However, the primary purpose of a premodulation filter is to limit RF spectral occupancy by attenuating the tails of the RF signal spectrum. Therefore a tradeoff of BEP for RF bandwidth is necessary. Figures 8 and 9 show the variation in BEP with premodulation filter bandwidth for f_B at 500 kb/s. Both figures suggest that the premodulation filter bandwidth should be set between $0.5f_B$ and $1.0f_B$. The relatively small losses in BEP for premodulation bandwidths as narrow as $0.5f_B$ are due to the band limiting of the IF filter. Since the sidebands of the RF signal spectrum are generally rejected by the IF filter, the premodulation filter should have little effect on BEP as long as its bandwidth is greater than $0.5f_B$ and the IF filter bandwidth is at optimum. Bandwidths less than $0.5f_B$ will cause a loss of signal power in the baseband that begins to severely degrade the BEP. A wider bandwidth than $1.0f_B$ will result in a relatively insignificant decrease in BEP because of the optimum IF filter's band limiting but will increase the RF bandwidth.

Figures 10 and 11 illustrate the difference in BEP between a premodulation filter set at $0.5f_B$ and $1.0f_B$ for f_B equal to 500 kb/s and with optimum IF bandwidths and RF deviations. The BEP variations with RF power were determined by incrementally varying the FM signal generator's attenuator and recording the attenuation and the BEP. RF power was calibrated to the attenuator by measuring high RF power levels at the receiver input with an RF power meter. There was a 0.4 to 0.6 dB improvement in BEP for NRZ using a 500 kHz premodulation filter over a 250 kHz premodulation filter and a 0.4 dB improvement for DM. At the non-optimum deviations in figures 10 and 11, the improvement was 1 dB for both NRZ and DM.

RF Bandwidth

IRIG document 106-73, Telemetry Standards, lists three RF channel bandwidths in the L- and S-band frequency ranges; they are 1.0 MHz, 3.0 MHz, and 10.0 MHz in width. These channel bandwidths are equivalent, as defined by IRIG, to RF signal bandwidths of 1.2 MHz, 3.2 MHz, and 10.2 MHz, respectively, where the signal is 60 dB down from the unmodulated carrier at the band edge. At each of several bit rates (with pseudo-random data), the premodulation filter was varied and the RF transmitter deviation held fixed at optimum to find the maximum allowable premodulation filter bandwidth that would still restrict the RF signal bandwidth to within one of the IRIG channels. Figure 12 defines approximate maximum premodulation filter bandwidths for various NRZ and DM bit rates such that the RF spectra remain within a 1.0 MHz or 3.0 MHz channel. Bandwidth limitations on the premodulation filter and the modulation section of the RF signal generator did not permit 10.0 MHz channel measurements. The RF signal spectrum width will vary with the NRZ or DM formatting and shift with transmitter drift; thus the premodulation filter was always set such that the RF signal was down 60 dB at the band edges of the IRIG channels. This left 100 kHz of bandwidth on either side of the signal spectrum to allow for spectrum variations and drift.

The lower diagonal line in figure 12 represents the lower limit on premodulation filter bandwidth as defined by $0.5f_B$. Thus the approximate highest bit rate in which the RF spectrum will remain in a 1.0 MHz channel is roughly 350 kb/s for pseudo-random NRZ and 220 kb/s for pseudo-random DM. For a 3.0 MHz channel, the highest bit rates are approximately 1.0 Mb/s for NRZ and 720 kb/s for DM. Higher and lower bit rates may be possible depending on the data sequence. For lower bit rates than these maximums, it is recommended that the premodulation filter be set as wide as possible, up to $1.0f_B$, without the RF signal spectrum exceeding an IRIG channel. While larger premodulation bandwidths are possible, they do not give a significant decrease in BEP for the increase in RF bandwidth. As an example, consider a 500 kb/s NRZ signal, figure 12 indicates that the premodulation filter can be set from 250 kHz to 850 kHz and still remain in the 3 MHz channel. Figure 10 shows a 0.4 to 0.6 dB improvement in BEP with a 500 kHz filter over a 250 kHz filter but no improvement over the 500 kHz filter with a 869 kHz filter.

If for a particular bit rate the RF spectrum is marginally within its RF channel and the premodulation filter is at $0.5f_B$, then it is possible to decrease the RF bandwidth by decreasing the RF transmitter deviation. By using figures 2 and 3, limits can be set on a permissible range of RF transmitter

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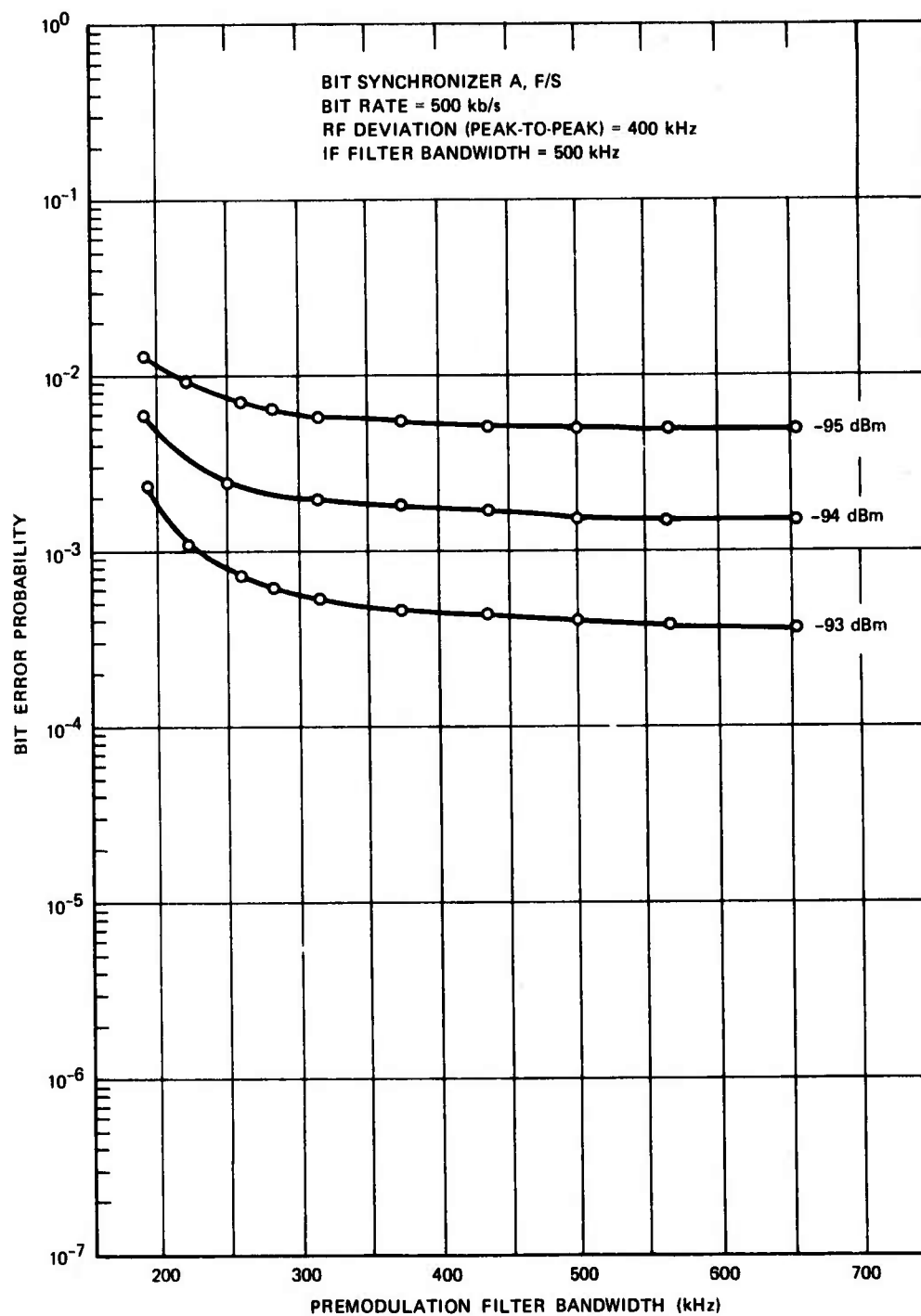
Figure 8. *NRZ BEP Variations With Premodulation Filter Bandwidth.*

Figure 9. *DM BEP Variations With Premodulation Filter Bandwidth.*

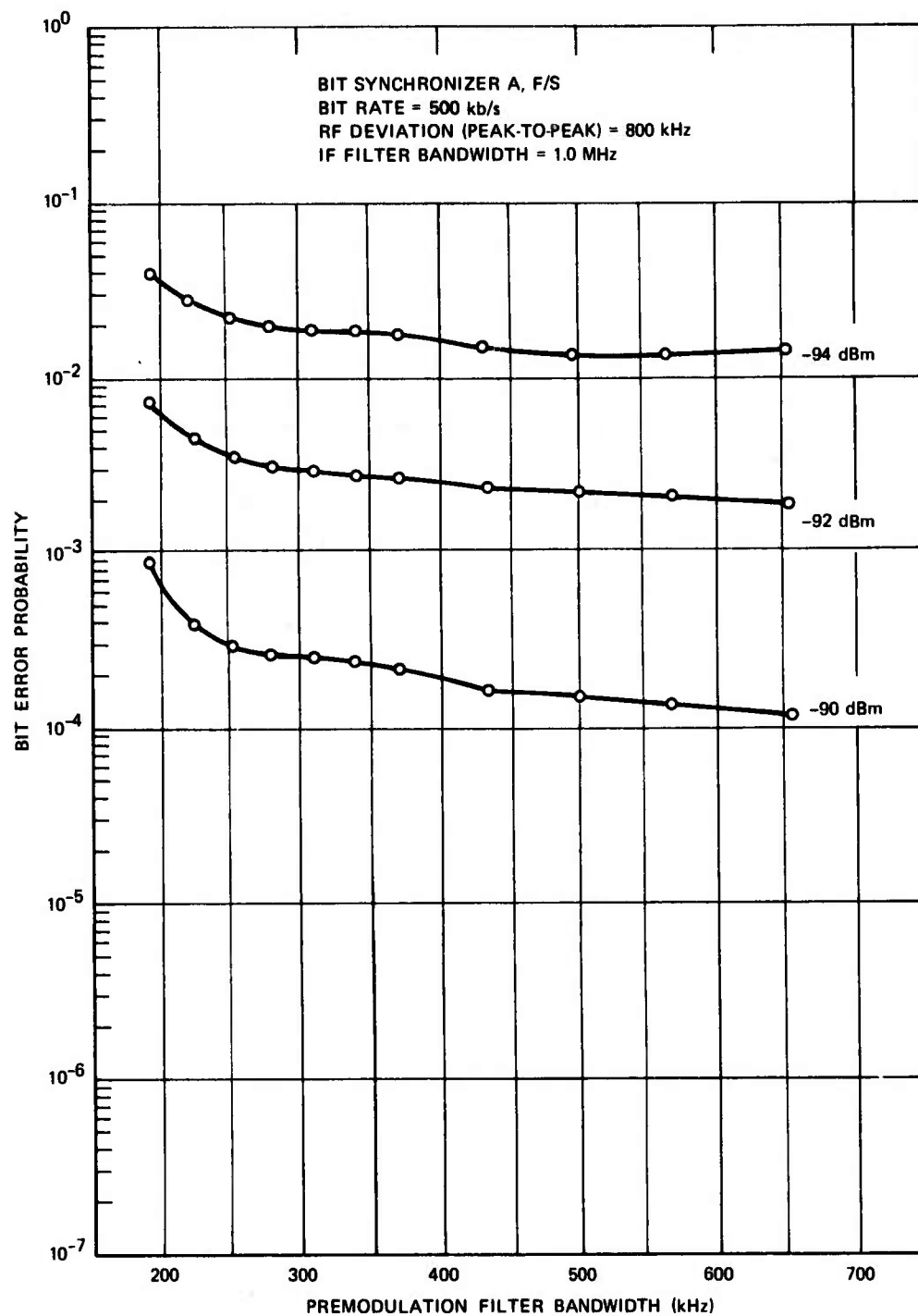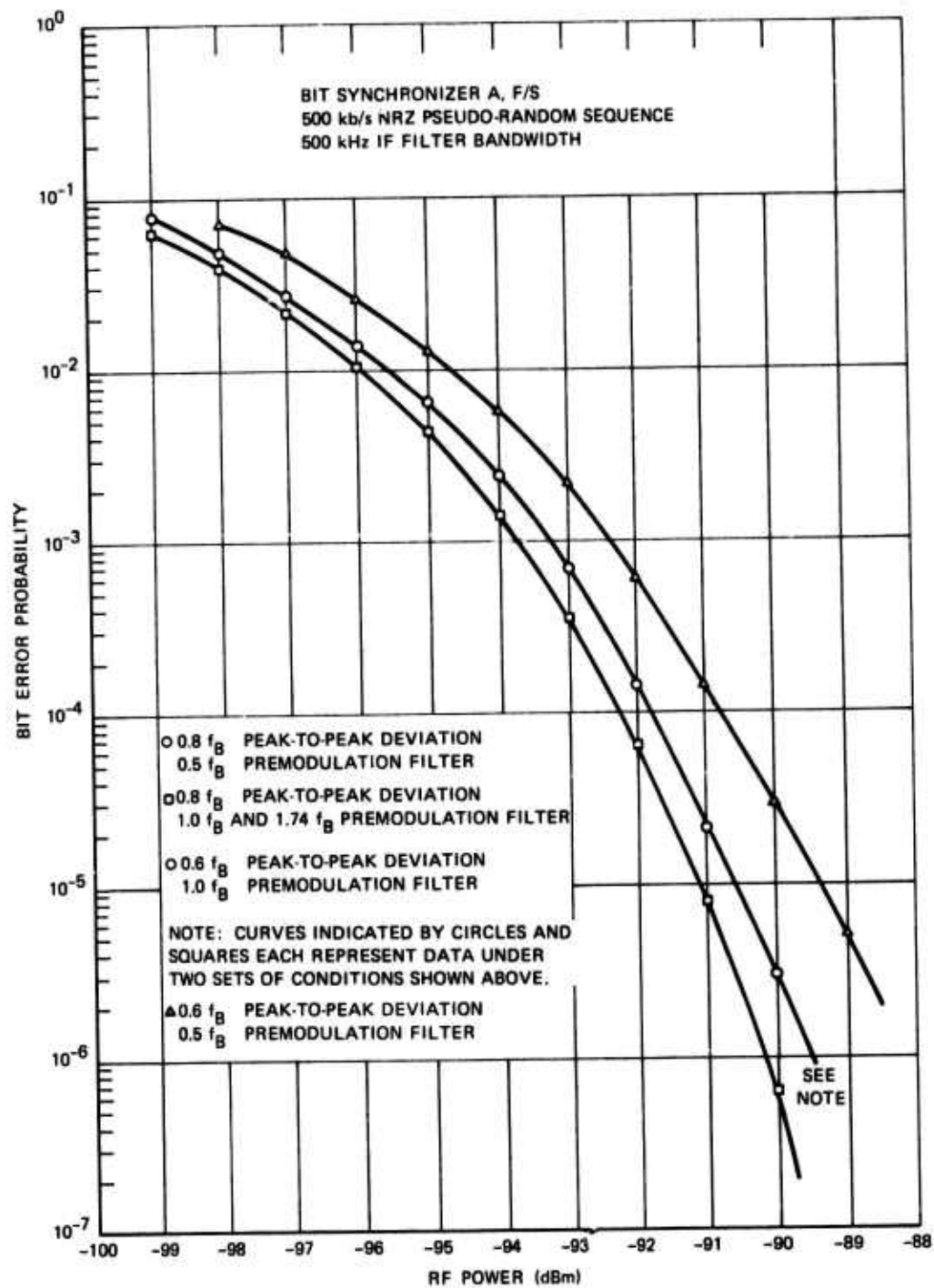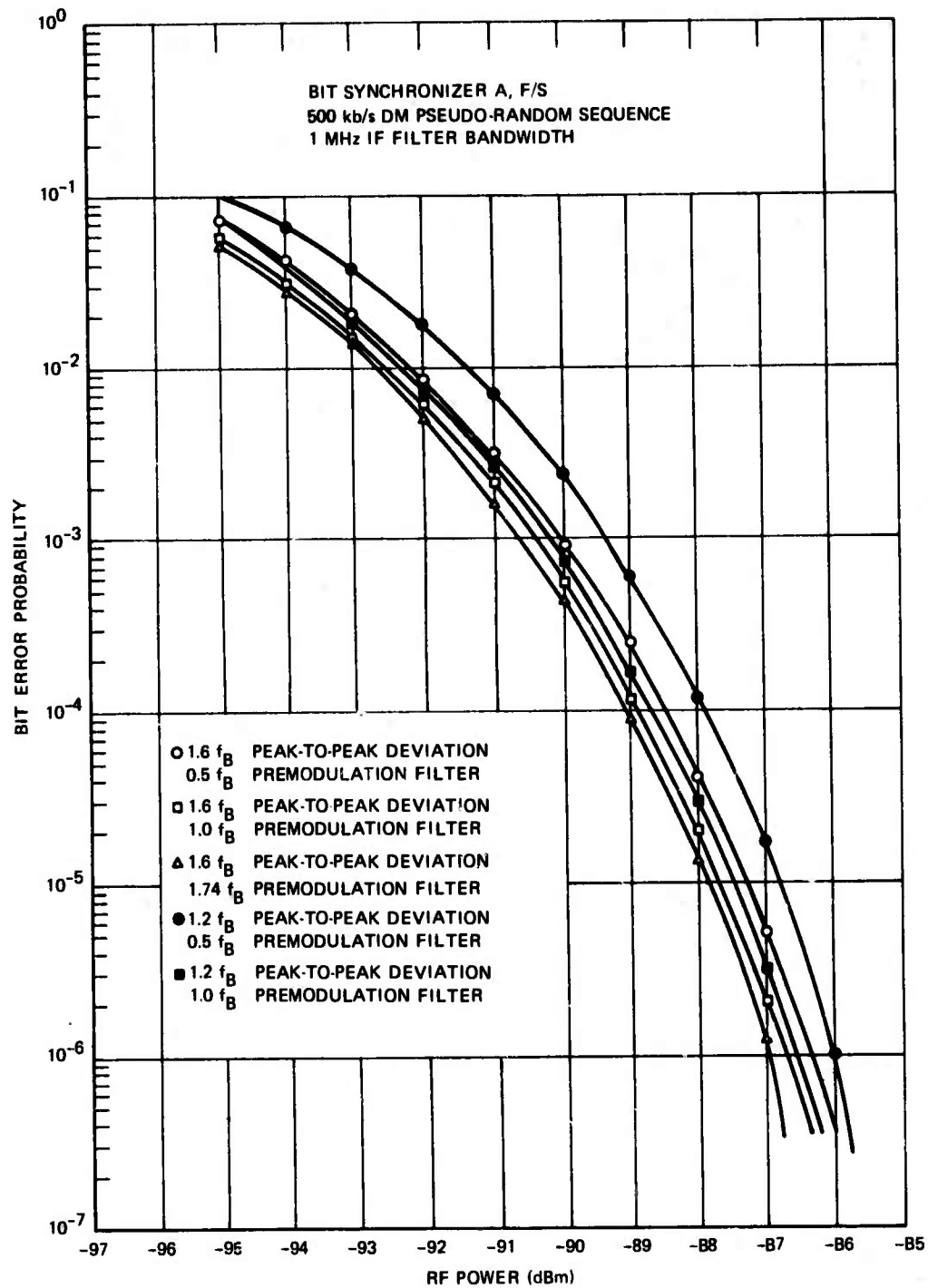Figure 10. NRZ BEP Sensitivity to RF Deviation and Premodulation Filter Bandwidth.

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Figure 11. DM BEP Sensitivity to RF Deviation and Premodulation Filter Bandwidth.

PSEUDO-RANDOM BIT SEQUENCE

NRZ ○ 1 MHz CHANNEL

NRZ ● 3 MHz CHANNEL

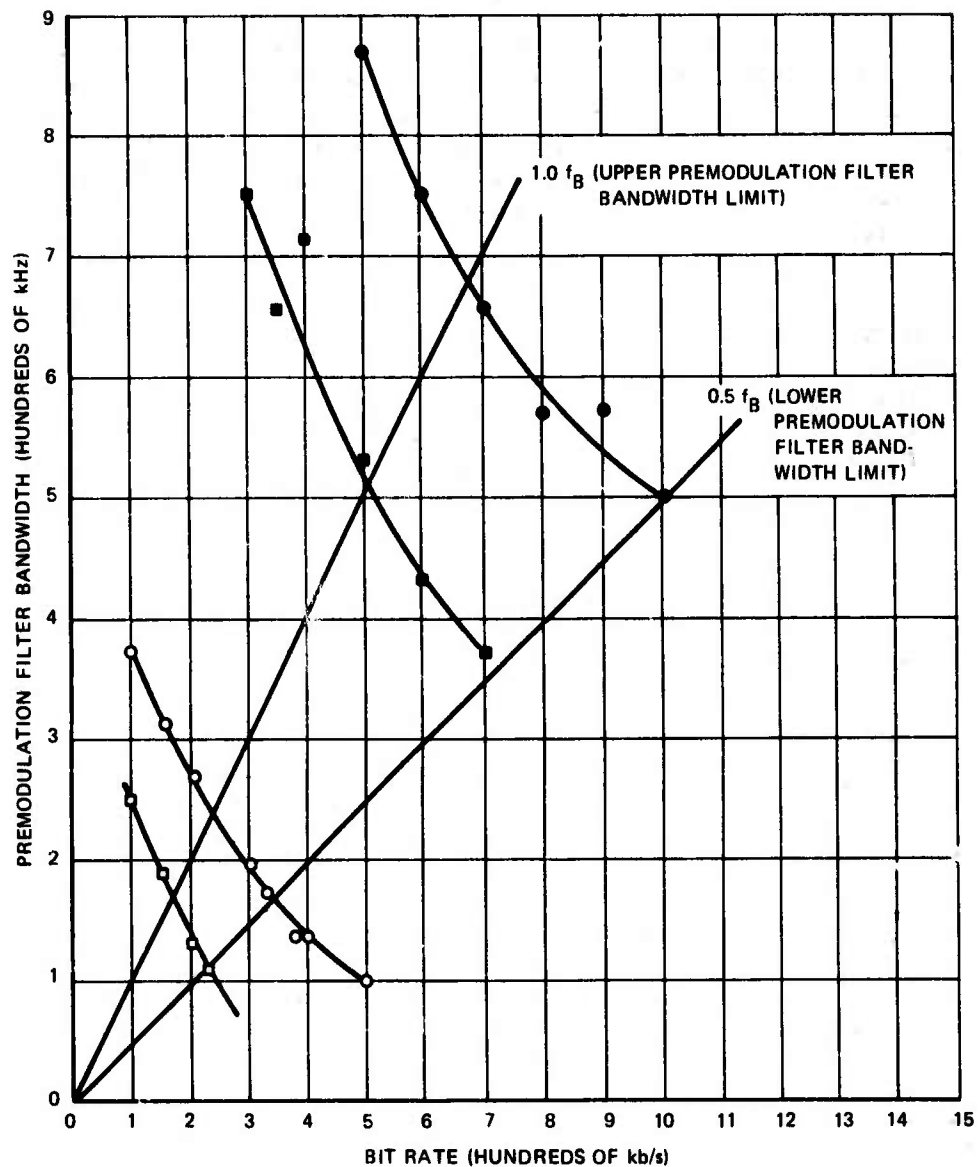DM   □ 1 MHz CHANNEL

DM   ■ 3 MHz CHANNEL

Figure 12. Bit Rates Containable in 1 MHz RF Channel Bandwidths by Band Limiting
With a Premodulation Filter.

deviation; the proposed limits are $0.6f_B$ to $0.9f_B$ for NRZ and $1.2f_B$ to $1.8f_B$ for DM. Within these limits, the BEP has been slightly degraded from that at the upper limit for a small decrease in RF bandwidth. Exceeding the upper limit increases not only the BEP but the RF bandwidth too, whereas dropping below the lower deviation limit begins to significantly increase the BEP for any further bandwidth savings. For the deviation ranges proposed above, an RF bandwidth savings of 100 to 200 kHz for NRZ and 200 to 400 kHz for DM can be realized if required.

Figures 10 and 11 show the tradeoff in BEP that results when decreasing the RF transmitter deviation to save RF bandwidth. With the premodulation filter at $0.5f_B$, there was a 1.0 to 1.2 dB improvement in NRZ BEP when using the optimum deviation of $0.8f_B$ compared to using the lower deviation limit of $0.6f_B$ and a 0.4 to 0.6 dB improvement with the premodulation filter at $1.0f_B$. With the premodulation filter set at $0.5f_B$, there was a 0.6 to 0.8 dB improvement in DM BEP using the optimum deviation of $1.6f_B$ instead of the lower deviation limit of $1.2f_B$ and a 0.2 dB improvement with the premodulation filter at $1.0f_B$.

NRZ AND DM

A description of the two PCM formats is given in figure 13 (see reference 6). Because of mid-bit transitions, DM is at twice the clock rate of NRZ. The optimum system parameters reflect this difference in RF deviation and IF bandwidth which for DM are twice those of NRZ; i.e.,

	NRZ		DM	
	F/S	I/D	F/S	I/D
P-P RF Transmitter Deviation	$0.8f_B$	$0.9f_B$	$1.6f_B$	$1.8f_B$
IF Filter Bandwidth (or equivalent pre- and post-recording IF BW)	$1.0f_B$	$1.0f_B$	$2.0f_B$	$2.0f_B$
Premodulation Filter Bandwidth	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$	$0.5f_B$ to $1.0f_B$

Figures 14 and 15 compare the video spectra of two PCM formats, and figure 16 compares the BEPs of 500 kb/s NRZ and DM under their optimum conditions. Figure 16 shows that the BEP for NRZ is approximately 3 dB better than for DM. This result agrees with those results reached by Dr. W. R. Hedeman of Aerospace Corporation in an unpublished report and by Dr. W. C. Lindsey of Southern California University in reference 6. Both reports conclude that, for a selected BEP, a given telemetry link can support twice the bit rate when NRZ is used as compared to the use of DM. This is experimentally verified by figures 6 and 7 where NRZ is twice the DM bit rate.

SUMMARY OF RESULTS

Optimum conditions for transmission of PCM/FM in general depend on the PCM code, the bit rate, the RF channel bandwidth, and system equipment. Optimum conditions are those system parameter values that minimize the BEP, subject to RF bandwidth requirements and system tolerances (i.e., transmitter and receiver drift). It was found that the optimum IF filter bandwidth is equal to the bit rate for NRZ and twice the bit rate for DM. However, under other than laboratory conditions, a wider-than-optimum IF bandwidth may be necessary because of the standard fixed IF filter sizes or because of transmitter and receiver drift. In fact, it is recommended that for tape-recording purposes, the receiver IF bandwidth be set wider than optimum to avoid IF clipping from signal drift and that a narrower filter bandwidth be used for data playback.
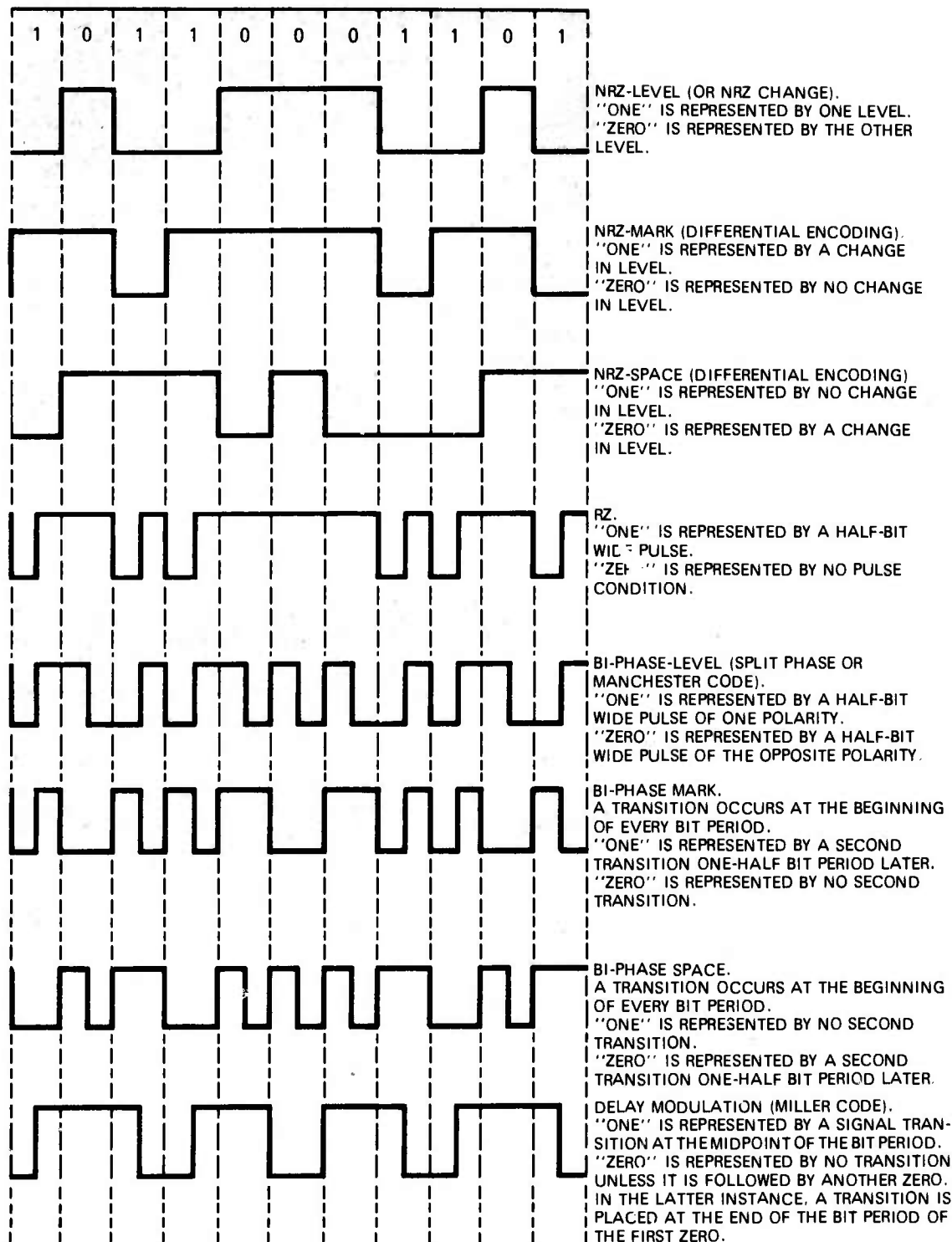
Figure 13. PCM Signaling Formats.

500 kb/s NRZ
500 kHz PREMODULATION FILTER
200 kHz/DIVISION

(a)

500 kb/s NRZ
250 kHz PREMODULATION FILTER
200 kHz/DIVISION

(b)

Figure 14. NRZ PCM Video Spectra of a Pseudo-Random Pattern.
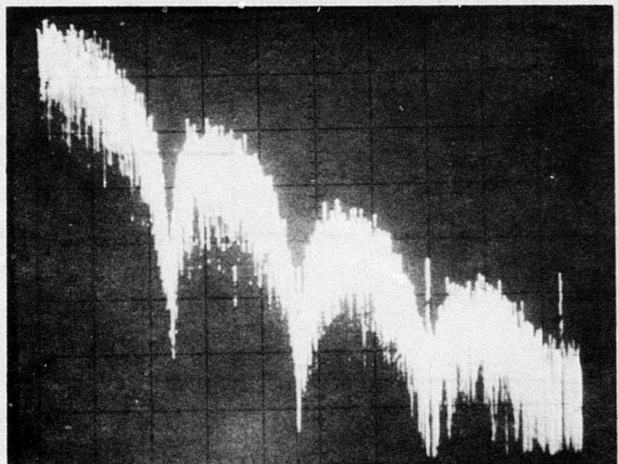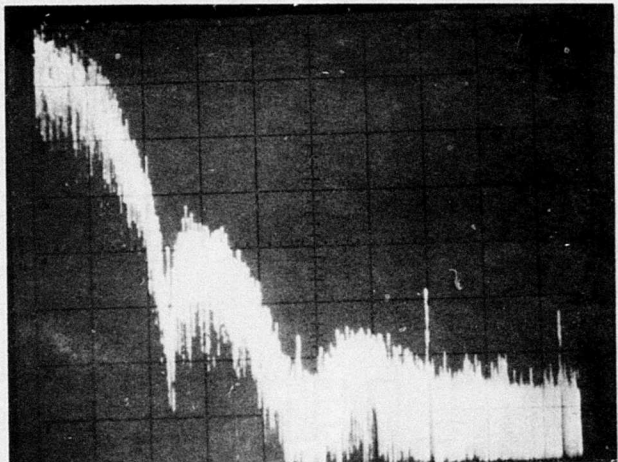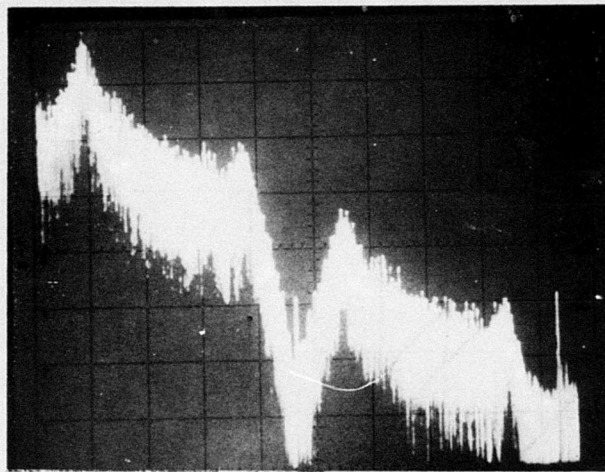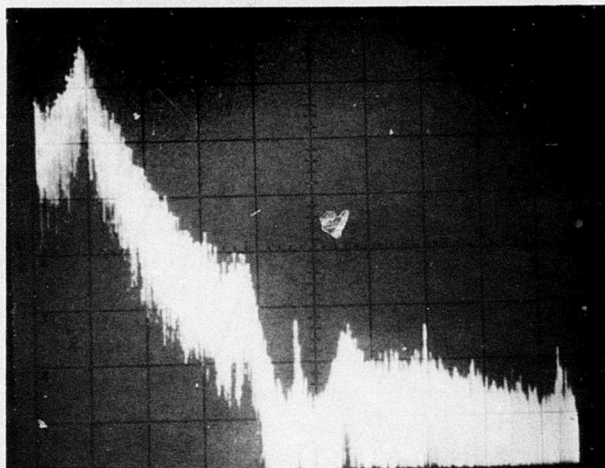
500 kb/s DM
500 kHz PREMODULATION FILTER
200 kHz/DIVISION

(a)

500 kb/s DM
250 kHz PREMODULATION FILTER
200 kHz/DIVISION

(b)

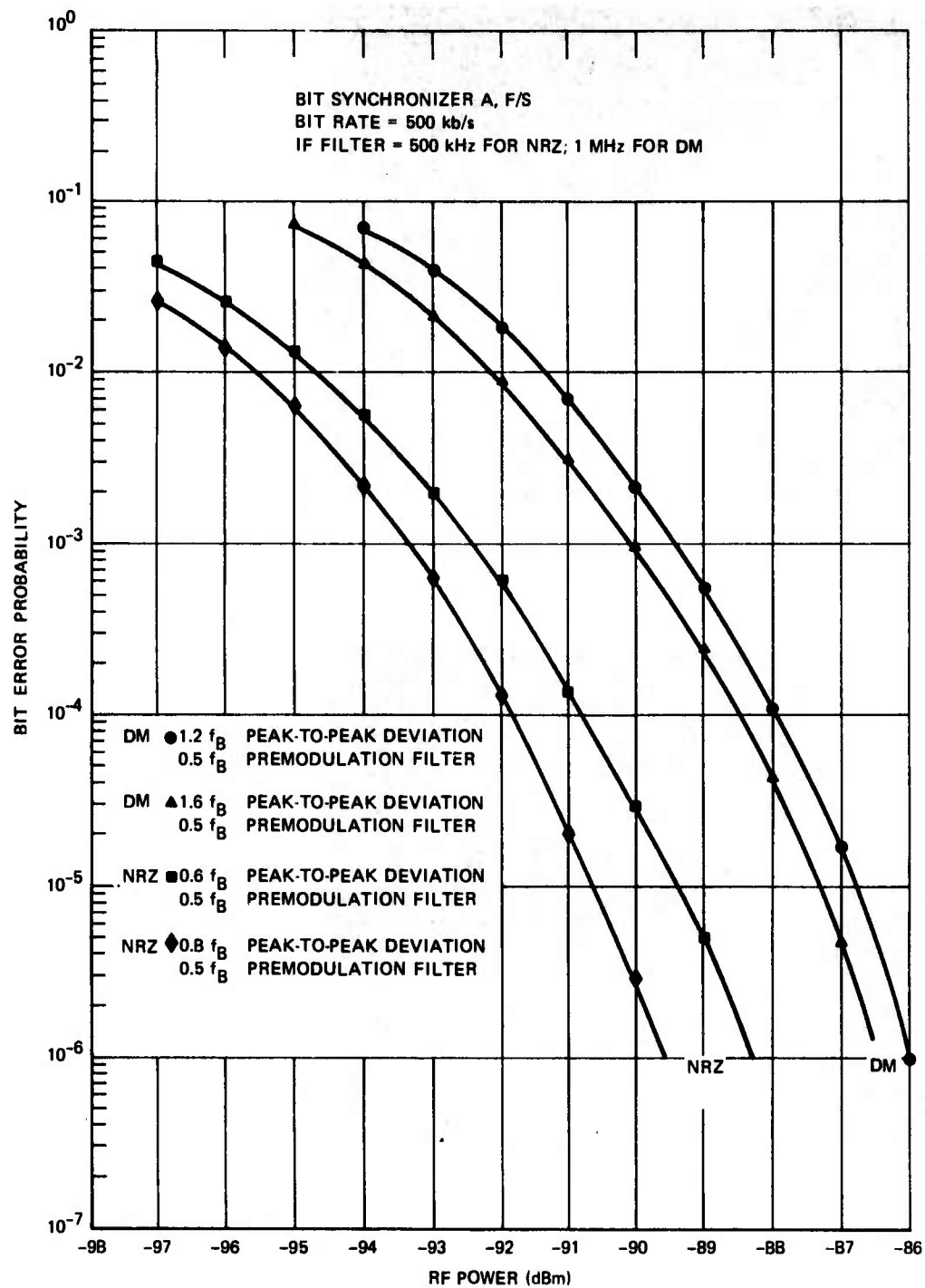Figure 15. DM PCM Video Spectra of a Pseudo-Random Pattern.

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Figure 16. Comparison of Optimum NRZ and DM PCM/FM Bit Error Probabilities.

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The optimum deviation is that deviation which minimizes the BEP within RF channel constraints. The optimum peak-to-peak RF deviation was found to depend upon IF filter bandwidth and bit detection equipment. Theoretical and experimental data (see references 1 through 5) indicate that the optimum deviation ranges from $0.7f_B$ to $0.9f_B$ for NRZ with an optimum IF filter bandwidth and may be higher for a wider-than-optimum IF filter.

The optimum premodulation filter bandwidth is a value which minimizes the BEP and keeps the RF spectral occupancy within requirements. Results show bandwidths less than $0.5f_B$ begin to severely raise the BEP and that bandwidths greater than $1.0f_B$ offer very little gain in terms of BEP. Because the premodulation filter's primary purpose is to bandlimit the RF signal spectrum, it should be associated with RF channel bandwidths as well as the bit rate.

Obviously, optimum conditions for data transmission can take on a wide range of values. Rather than attempting to achieve maximum performance from a system by determining optimum conditions for every requirement, rules of thumb for setting system parameters can be established for all systems in noncritical applications with only a moderate loss ($\sim$2 dB) in BEP. That is, many telemetry system applications must tolerate non-optimum operation to some degree. For these applications, rules of thumb may be used to facilitate the determination of system parameters. Such rules were given earlier in this report under Test Methods and Results. In general, the parameter values given by various rules of thumb should fall within the following ranges:

1. The receiver IF bandwidth should be at least twice the optimum for data-recording purposes. The equivalent bandwidth of the prerecording and post-recording IF combination should be close to f_B but less than $2f_B$ for NRZ and close to $2f_B$ but less than $4f_B$ for DM.

2. The peak-to-peak RF transmitter deviation should lie between $0.6f_B$ and $0.9f_B$ for NRZ and between $1.2f_B$ and $1.8f_B$ for DM.

3. The premodulation filter bandwidth should fall between $0.5f_B$ and $1.0f_B$ for both NRZ and DM.

This investigation verifies the conclusions of Dr. Lindsey (reference 6) and Dr. Hedeman that for equivalent bit rates under their optimum transmission conditions NRZ is 3 dB better than DM; for equivalent BEP, the bit rate of NRZ is approximately twice that of DM. Thus DM is not recommended for applications of maximum data transfer over a bandlimited RF system where noisy signals may be received.

REFERENCES

1. Kotel'nikov, V. A. "The Theory of Optimum Noise Immunity." McGraw-Hill, N.Y., 1960.

2. Smith, E. F. "Attainable Error Probabilities in Demodulation of Random Binary PCM/FM Waveforms;" IRE Transactions on Space Electronics and Telemetry. Vol. SET-8 (Dec 1962) pp. 290-7.

3. "Telemetry System Study" Final Report, Aeronutronic Publication U-743 (Dec 1959); U.S. Army Signal Research and Development Laboratories Contract No. DA-36-039 (SC-73182) Proj. No. 3-16-00-300.

4. Electro-Mechanical Research Inc. "Experimental Determination of Signal-to-Noise Relationships in PCM FM and PCM PM Transmission," by L. R. Brown. NASA Contract NAS 5-505, 20 Oct 61.

5. Shaft, P. D. "Error Rate of PCM-FM Using Discriminator Detection," IEEE Transactions on Space Electronics and Telemetry: Vol. SET-9 Dec 1963. pp. 131-7.

6. Naval Missile Center. Bit Synchronization System Performance Characterization, Modeling, and Tradeoff Study, by W. C. Lindsey. Point Mugu, California. 4 Sep 1973 (Technical Publication TP-73-18) UNCLASSIFIED.

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